A QUALITATIVE DISCUSSION OF THE STABILITY AND CONTROL OF VTOL AIRCRAFT DURING HOVER (OUT OF GROUND EFFECT) AND TRANSITION

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ABSTRACT

A survey of the latest available literature was made in order to qualitatively discuss stability and control problems of vertical takeoff and landing (VTOL) aircraft during hover (out of ground effect) and the transition to level flight. Modes of propulsion and methods of performing the transition maneuver are discussed. Comparisons are made of the various methods utilized for providing control forces at zero and very low speeds. The need for quantitative control power requirements and handling qualities criteria is presented. The instability of VTOL aircraft while hovering is discussed, as are the basic reasons for the poor damping characteristics at low speeds. Problems which have been encountered to date with research aircraft and which are peculiar to a given VTOL mode are discussed by mode. The need for automatic stabilization and precision instrumentation requirements are presented.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1. Introduction

During recent years, a significant trend has developed in the performance objectives of airplane design. In addition to the emphasis on extending high-speed capabilities, there is now concerted effort to reduce takeoff and landing airspeeds in order to develop safer and more versatile aircraft. The ultimate in this direction is an airspeed of zero, with the aircraft possessing the capability of performing vertical takeoffs and landings (VTOL).

The primary advantage of civil VTOL aircraft is their capability of operating out of smaller airports than can their conventional counterparts. This obviates the need for extension of runways at existing airports, or the purchase of large areas of expensive land for new airports, in order to provide a community with modern air transport facilities. Another advantage, both to operators and to nearby residents, is the large reduction in ground noise level made possible by the utilization of the steep descent and climb-out capability of the VTOL aircraft.

The VTOL airplane has great potential value in its military applications. The most obvious advantage is its utilization in delivering ground troops and supplies, the requirement being only that a clearing of sufficient size exist in a reasonably level region. Tactical close air support VTOL airplanes can operate in close proximity to zones of action out of these same clearings, thus reducing the time required to deliver ordnance on a target, or the number of airplanes

required airborne on station. Destruction of or damage to airfield runways loses significance if the aircraft utilizing the field have a VTOL capability. Consistent with weight and size limitations, each VTOL airplane is capable of shipboard operations, without the requirement for arresting hooks, catapult fittings, and the usually associated structural beef-up. By the same token, many ships, with the relatively simple addition of a landing area, are capable of operating VTOL airplanes without the requirement for heavy and complicated arresting and catapult systems.

Another advantage of the VTOL airplane is its ability to make steeper approaches under instrument conditions, thus providing greater obstacle clearance with no increase in rate of descent. Since VTOL aircraft of necessity have greater thrust-to-weight ratios than conventional airplanes, their waveoff capability is much improved.

One of the major design problems in VTOL aircraft is the provision of a VTOL capability without unduly compromising payload, range, or speed. In order to accomplish this, many methods or modes of providing the VTOL capability have been investigated, and these methods will be discussed in more detail in the next section. The final choice of which mode is to be used for a particular aircraft depends on a trade-off of mission requirements and desired aircraft performance.

With the current interest in VTOL aircraft, and since certain of the configurations have demonstrated stability and control deficiencies during hover and the transition to level

flight, a survey of the present day literature was made to determine the basic causes of these deficiencies. Since stability and control characteristics depend on the particular configuration and mass distribution of the particular airplane, the results of this survey are necessarily of a qualitative nature. The influence of ground effect was not investigated.

The term "transition" as used in this report is defined as the flight regime from hover to an airspeed at which wing-supported flight can be safely and easily performed under power-off conditions. The term "conversion" was used in some of the early literature in the same sense as transition, but is now generally used to denote the mechanical configuration changes made to the aircraft to permit transition from VTOL operation to translational wing-supported flight.

This work was accomplished during the period February - April 1964 at the U. S. Naval Postgraduate School, Monterey, California.

2. Methods of Providing VTOL Capability.

General

All hovering aircraft support themselves by accelerating air downward. A helicopter imparts a low velocity to a large diameter stream of air, while a jet VTOL aircraft imparts a high velocity to a small diameter stream of air. In any case the thrust is given by $T = mV$, where V is the exhaust velocity and m is the mass flow per unit time. It has been shown that a rotor configuration is dictated if there is a requirement for long hovering times, and that aircraft utilizing jet engines can economically hover only the $1\frac{1}{2}$ to 2 minutes required for takeoff and landing [31].

In general, there are four basically different types of propulsion systems used to produce the required vertical thrust; these are the rotor, the propeller, the ducted fan, and the turbojet. The distinction between rotors and propellers is often very difficult to make. The most satisfactory arbitrary definition is that if cyclic pitch is used for control in hovering flight, the device is a rotor; otherwise it is a propeller. Rotorcraft were not considered in this survey due to the extensive amount of work already performed with helicopters and associated designs. Rotors generally provide high drag and become inefficient at relatively low airspeeds, so that the maximum airspeed of rotor-powered aircraft is usually considerably less than that of the other types.

A further classification of VTOL aircraft can be based on the means utilized to perform the transition from hovering

to level flight. There are four fundamental principles involved in transition, although some aircraft employ combinations of two or even three of these principles. The four basic transition means are aircraft-tilting, thrust-tilting, thrust-deflection, and dual-propulsion. The aircraft-tilting type, more commonly known as "tail sitters" or "Pogo", are not considered in this report due to the general abandonment of interest in this type. The major drawback to this configuration was that the pilot was essentially lying on his back, and had to look back over his shoulder in order to see the ground during takeoffs and landings. The other modes perform takeoffs and landings with the fuselage essentially horizontal at all times. Thrust-tilting aircraft tilt the thrust unit itself, while thrust-deflecting aircraft have provisions for deflecting the slipstream or jet exhaust. Dual propulsion configurations utilize one method of propulsion to provide thrust for vertical flight, and another method for horizontal flight.

Thus, in considering three types of propulsion systems and three transition methods, the result is nine possible airplane types. However, the dual-propulsion propeller type has received practically no investigation. This leaves eight primary modes, each of which is represented in Fig. 1, and which will now be discussed in more detail.

Propeller aircraft.

Thrust tilting.

Thrust-tilting can be accomplished in two basic ways; either the propulsive unit itself can be rotated relative to

PROPELLOR AIRCRAFT

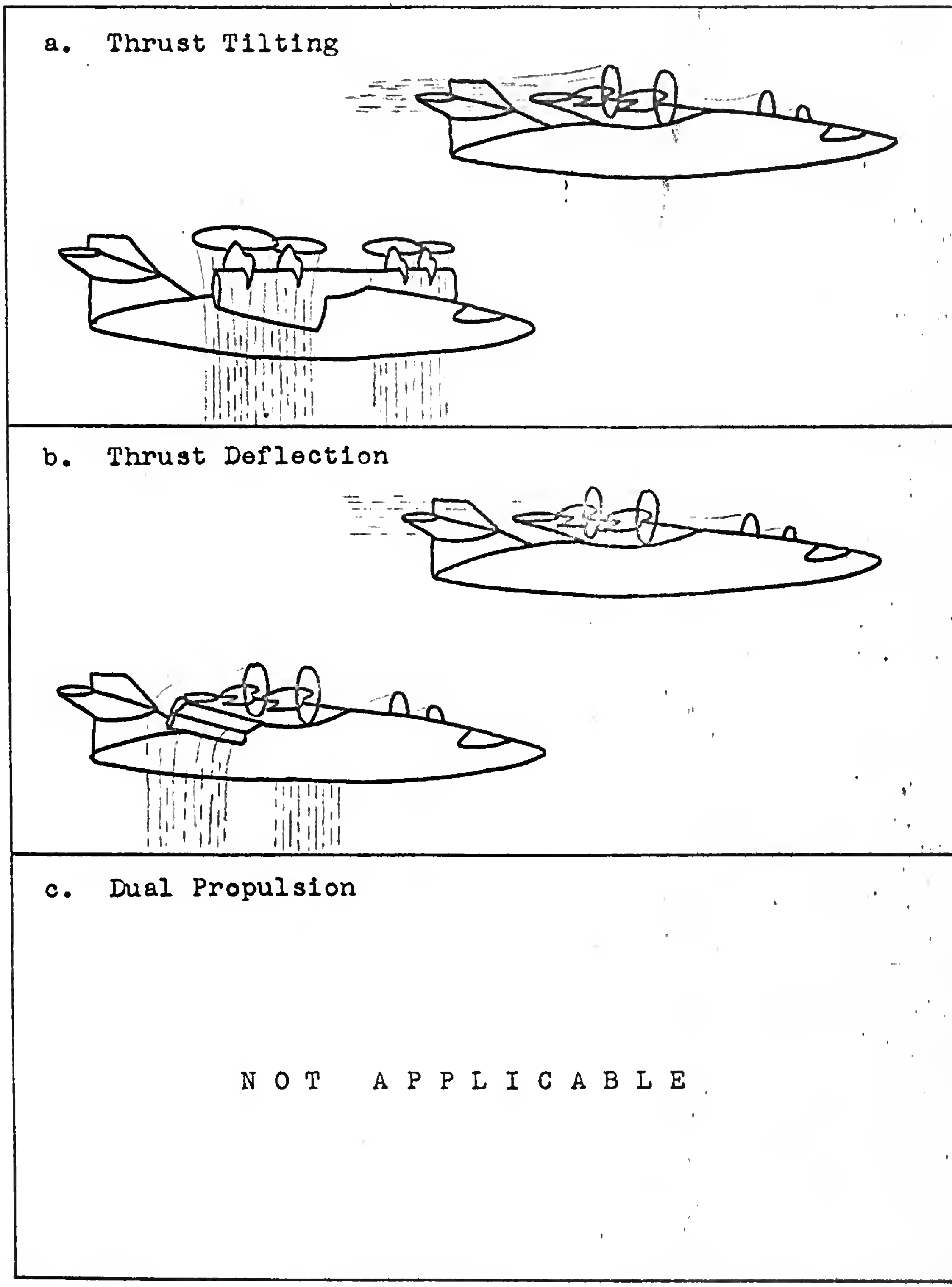

FIGURE 1

BASIC TYPES OF VTOL AIRCRAFT

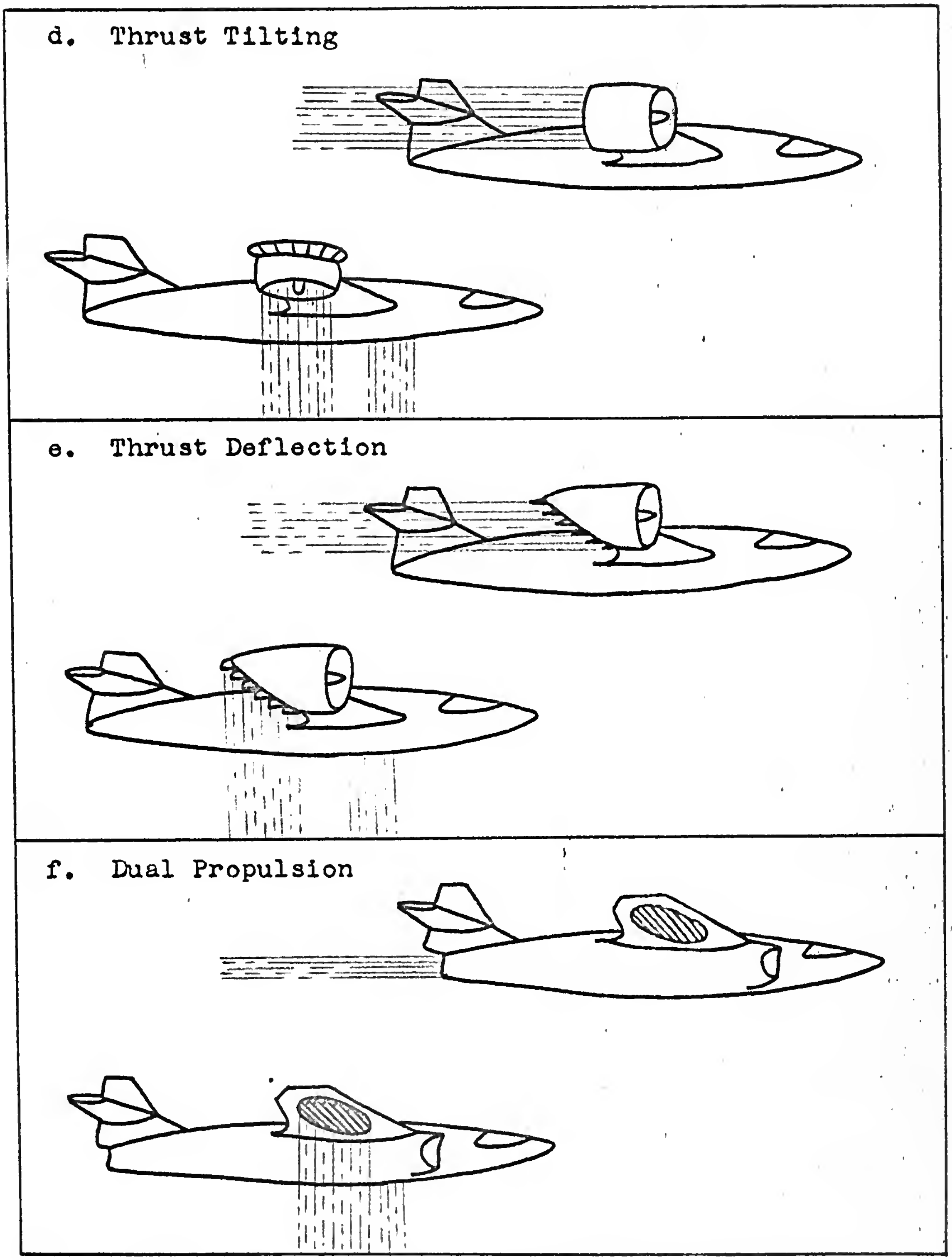

FIGURE 1

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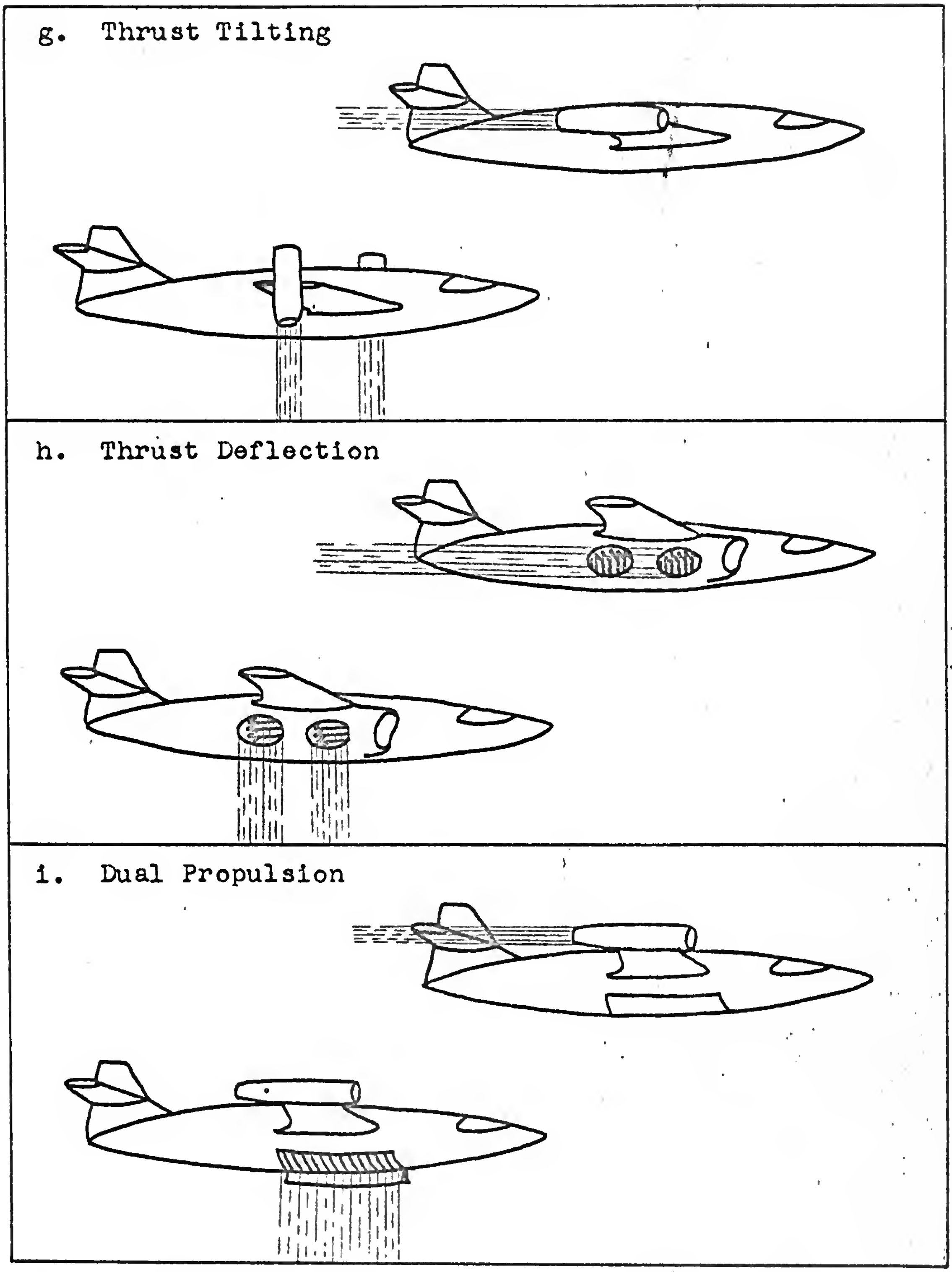


FIGURE 1

(Concluded)

the rest of the airplane, or the entire wing, complete with propulsive units, can be rotated relative to the airplane fuselage. Tilt-prop aircraft have been built, but are inferior to the tilt-wing configuration in that if the wing is located within the propeller slipstream, that portion of the slipstream is ineffective in producing lifting thrust due to impingement on the wing. If the wing is not located in the slipstream, then the advantage of reducing effective angle of attack over portions of the wing, especially in steep, low-speed descents, is lost.

Providing a tilt-wing capability results in increased airplane complexity and weight. Engine, aileron, and flap controls routing must be reckoned with, and the wing tilt mechanism is an added weight factor. Tilt-wing VTOL airplanes encounter problems in the transition phase due to wing stalling. This problem is discussed in more detail in Section 5. The operation of the tilting elements of various configurations, including tilt-wing, has been found to be little more complex than the operation of flaps and speed brakes on conventional airplanes [32]. Further, if the switch for operation of the tilting elements is located on the control stick, tilt can be accomplished without the pilot removing his hands from any of the primary controls.

Deflected slipstream.

Turning a slipstream a full 90 degrees by use of flaps or vanes usually results in losses as high as 50 percent when hovering. If the slipstream is turned only 60 degrees, and

the remaining 30 degrees of turning achieved by tilting the thrust unit or the airplane itself, a well designed airplane could incur turning losses of only approximately ten percent. However, as depicted in Fig. 2, these losses decrease rapidly and power required consequently decreases with forward speed. Deflected slipstream alone can thus be seen to be a promising means of providing a short takeoff and landing (STOL) capability.

It can be seen from Fig. 2 that a combination of tilt-wing and deflected-slipstream could utilize the best features of each mode. The wing would be rotated 90 degrees with no flap deflection for hovering flight. As transition commenced, the flaps would be extended to take advantage of the deflected-slipstream characteristics. This technique does show promise, and will be discussed in more detail in Section 5.

Ducted fan.

A ducted fan is defined generally as a propeller or fan within a shroud or duct. Arrangements consisting of a propeller within a shroud have been referred to as shrouded or ducted propellers, while highly loaded fans installed within ducts in the wing or fuselage of the airplane have been termed buried fans. These varied installations are now generally considered as being variations of the ducted fan. Turbofan engines are usually not classed as ducted fans since they involve the use of a very highly loaded fan integrated into the design of the basic engine.

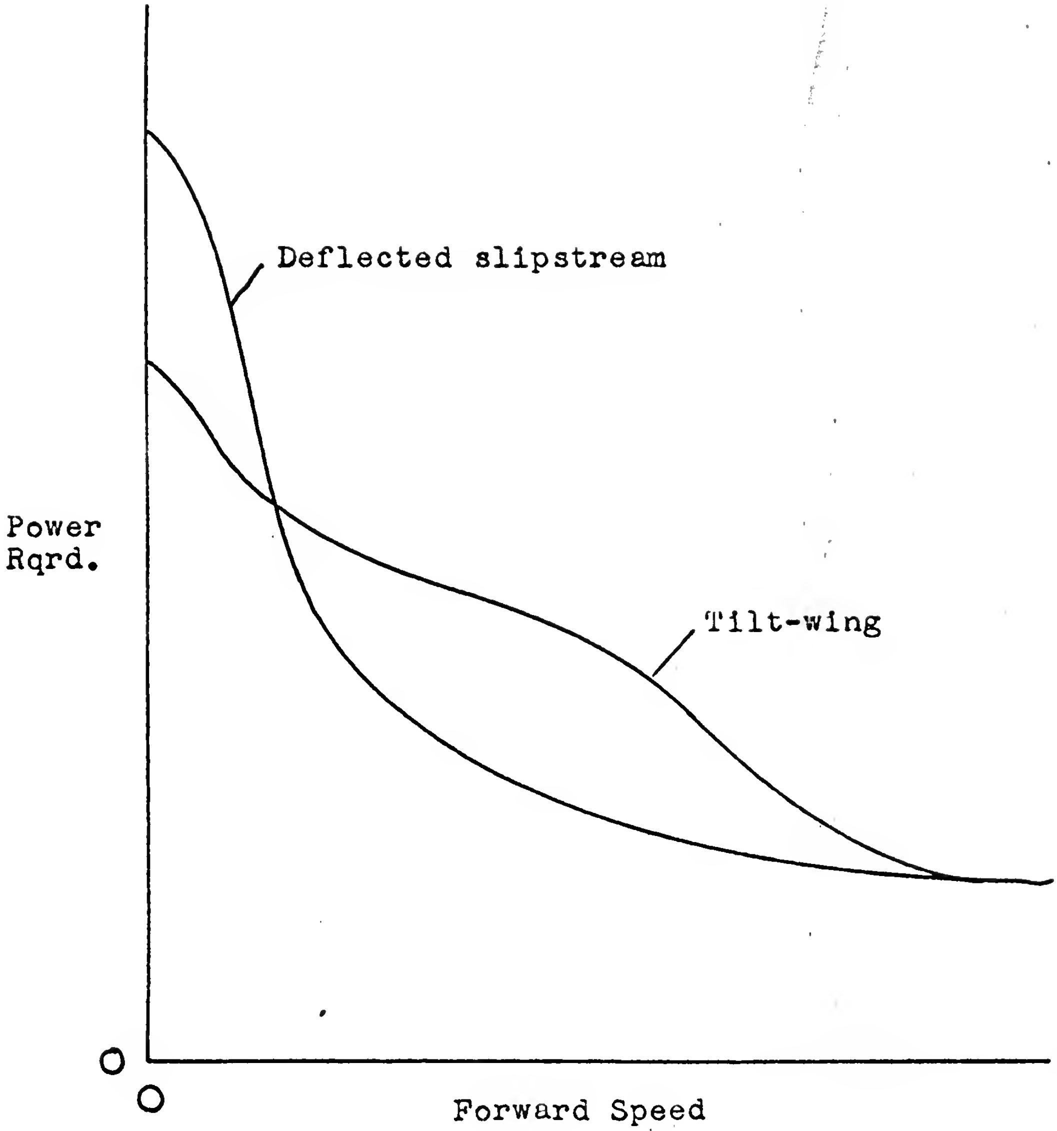


FIGURE 2

POWER REQUIRED IN TRANSITION (TYPICAL)

Thrust tilting.

Most tilt-duct airplanes have the ducts mounted on pivots at the wingtips. The fans are in the vertical position for takeoff and landing, and are rotated downward to serve as propellers for forward flight. The ducts permit the use of a smaller diameter propeller to provide a given thrust and power, and tests have shown that a five-foot diameter duct on the tip of an eight-foot semispan wing, under windmilling conditions, nearly doubled the lift coefficient of the wing alone [34]. However, at moderate airspeeds with the ducts at partial tilt, the ducts carry an increasingly greater part of the total lift, while the proportion of lift provided by the wing decreases. This non-uniformity of lift distribution results in a higher power requirement for a given airspeed.

Deflected slipstream.

Some deflected-slipstream installations have been wind-tunnel tested, but as with the propeller version, considerable thrust losses are incurred in turning the flow. To date, this type of propulsive unit has been inferior to tilt-duct installations from the standpoint of efficiency in the hover and at low transition speeds, and has not been seriously considered for VTOL application.

Dual propulsion.

Dual-propulsion ducted fan arrangements are usually referred to as buried-fan or, more commonly, fan-in-wing or fan-in-fuselage. The fans provide the lift for vertical flight, and a separate engine, usually turbojet, provides the thrust

for horizontal flight. The fans are covered over, both inlet and exit, during cruising flight, in order to reduce the drag. Although separate propulsive units can be used for the vertical and horizontal thrust units, it is now commonplace to use the same gas turbine powerplant for both functions. During vertical flight, the gas is diverted and directed to a series of turbines mounted on the tips of the fan blades (referred to as the fan turbine scroll). During transition to level flight, exhaust flow is increased to the jet engine nozzle, while the flow to the lift fan is decreased, until all the gas is exhausting through the jet nozzle at the completion of transition.

Turbojet.

The turbojet classification includes turbofan engines, as discussed previously. Turbofan engines have variously been referred to as by-pass, fan, or ducted-fan jet engines. The distinguishing feature of a turbofan engine is the presence of a concentric fan, usually at the forward end, which serves as a compressor to provide a high-pressure cold air exhaust which is used to augment the hot exhaust. A recent development incorporates plenum chamber burning in the fan-compressed air for further thrust augmentation [14]. In some turbofan engines designed specifically for VTOL application, the fan and the straight-through compressor rotate in opposite directions in order to reduce gyroscopic effects.

Another development brought about by VTOL requirements has been the small, lightweight turbojet "lift" engine. These

engines are mounted vertically, and are utilized to provide lift only during the takeoff, landing, hover, and transition phases. These engines will almost always be operated at low altitudes and airspeeds, and over a restricted thrust range. They also will have only a short running time, probably less than three minutes per flight at full power. Due to these requirements, which are much less stringent than those imposed on the primary engines, the lift engine can be made mechanically simple with corresponding weight reduction. Current operational designs provide thrust-to-weight ratios of approximately 16:1.

Thrust tilting.

The thrust-tilting jet airplanes built to date have utilized podded engines mounted on pivots at the wingtips or on the sides of the fuselage. Except for an early research aircraft, none have employed thrust tilting alone.

Deflected thrust.

All functional deflected-thrust jet engines utilized to date have employed the same basic feature, rotatable nozzles or vanes which are used to direct the exhaust gases in the desired manner. A typical scheme is depicted in Fig. 3. These thrust diverter devices direct the jet exhaust straight down for vertical flight. The pilot controls the diverter angle during transition, until they are directing the thrust rearwards for level flight.

An additional advantage can be realized from the deflected-thrust turbofan arrangement if the fan exhausts under and in

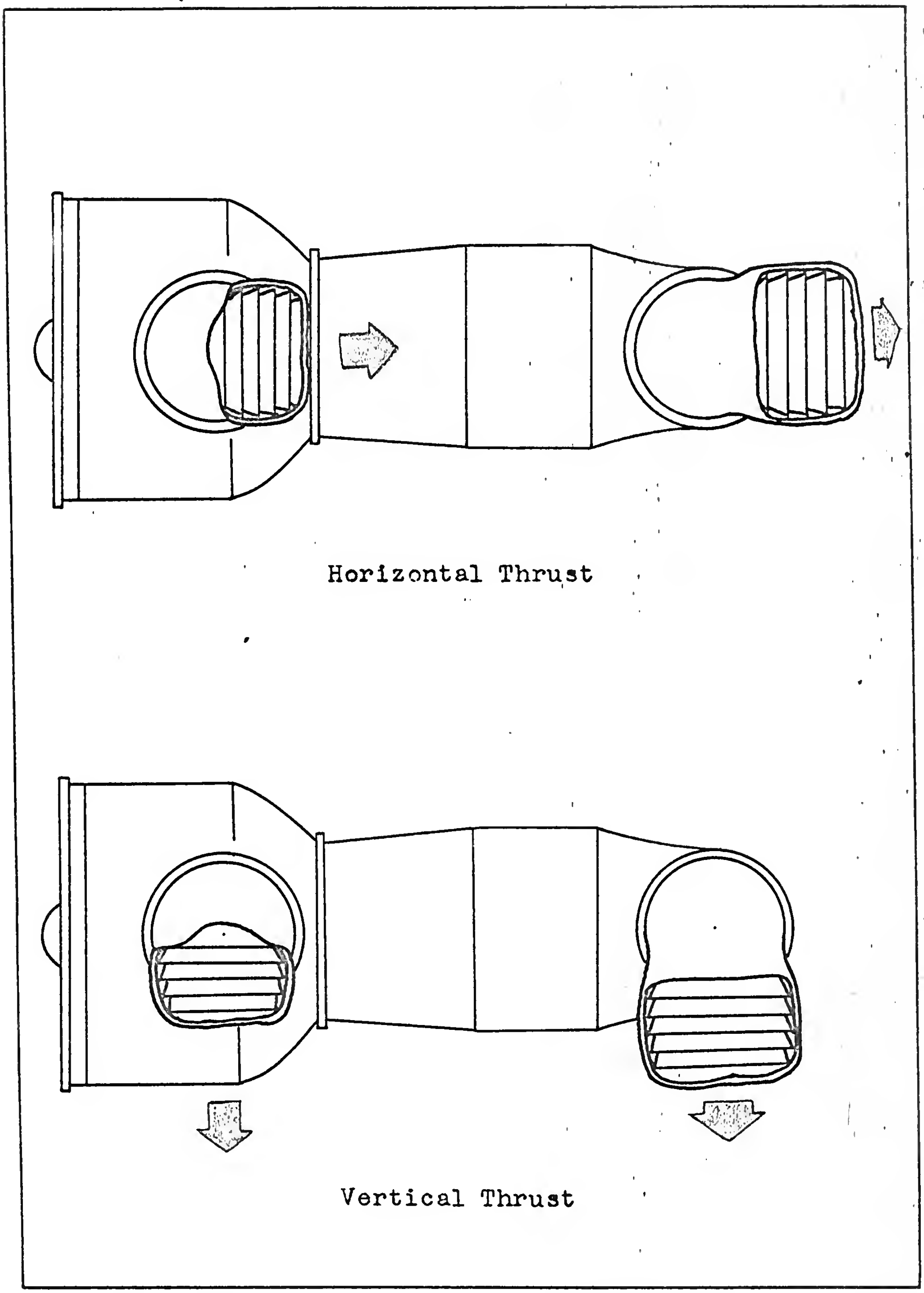


FIGURE 3

DEFLECTED THRUST TURBOFAN ENGINE

fairly close proximity to the wing. It would be possible to direct this airflow slightly upward and through the slot of a slotted flap, thereby producing an external-flow jet-augmented flap. This technique may prove worthwhile when high lift coefficients are required at low airspeeds, such as in holding patterns or during conventional or STOL approaches.

Dual propulsion.

With the advent of high thrust-to-weight ratio lifting engines, the dual-propulsion scheme is rapidly gaining in favor for application to jet VTOL aircraft. Many applications combine all three propulsive modes, in various combinations. An example might be an airplane with tiltable pods on the wingtips, fuselage-mounted lift engines with limited exhaust deflection, and fuselage-mounted deflected-thrust engines. As borne out in Ref. [14], the combinations are limited only by the hardware available, and the imagination and ingenuity of the designer.

Another type of dual-propulsion scheme utilizes the augmented jet, or jet pump principle. In this mode, jet engines are utilized or provide thrust for cruising flight. For vertical or hovering flight, the engine exhaust is diverted and ducted to nozzles which discharge the gases downward through mixing chambers. This primary nozzle flow induces a secondary flow of ambient air, and both combine to provide the required lift force.

3. Aircraft Control.

In the hovering and very low forward speed regimes, aerodynamic forces have only small influence on the stability characteristics of a VTOL aircraft. Under these conditions, the characteristics of the controls and the response of the aircraft to control inputs are of prime importance. Also, conventional aerodynamic controls which depend on freestream dynamic pressure to provide forces are naturally ineffective in this speed regime. The various methods of providing control forces and the applications to control about each of the three axes will now be discussed.

Methods of providing control forces.

Generally, for hovering and low-speed flight, it is desired that only couples be produced, and that the net force be zero. This is to forestall any undesirable translational motions or changes in lift which might otherwise occur in precision flying maneuvers. Thus net control forces are often applied in equal and opposite pairs, one being either side of the aircraft center of gravity.

The first and probably most widely used method of providing control forces is by the use of reaction nozzles which develop a thrust in the direction desired. Self-contained jets have not found favor in the VTOL field, probably because of the availability of an engine-produced air supply. Also, if sufficient fuel were carried to provide for repeated demand for large forces an additional weight factor is introduced, and airplane servicing is made more complex.

Nozzles operating from engine bleed air may be low-powered "puffer pipes" for continuous, limited-authority stabilization and rate-demand control, or may be high-powered for exerting maneuver control moments. The latter are sometimes only transient demand controls, since the amount of bleed air taken from the engine must be carefully restricted in order to preserve engine performance. High-powered nozzles may in some cases have a separate source of air, either ground-serviced, or charged and maintained by engine bleed air. Nozzles may be uni- or bi-directional, and may seal in their mid positions, bleed continuously, or pulse.

Nozzles which operate only on demand are advantageous as long as they are not operating, since no air is bled from the engine. However, once a control is actuated, engine thrust is reduced. Even if the nozzle force is upward, ducting and nozzle losses result in a net reduction in lift force. However, where these losses are acceptable, the demand nozzle is sometimes utilized.

Continuous-flow controls require a variable nozzle to effect thrust changes, thus increasing their complexity, but have the advantage of utilizing a constant bleed air rate. A method by which a moment may be produced by constant bleed rate nozzles without a net total force change is depicted in Fig. 4.

Pulse-jet arrangements, like constant-bleed nozzles, must of necessity operate in pairs. The pulse of air alternates

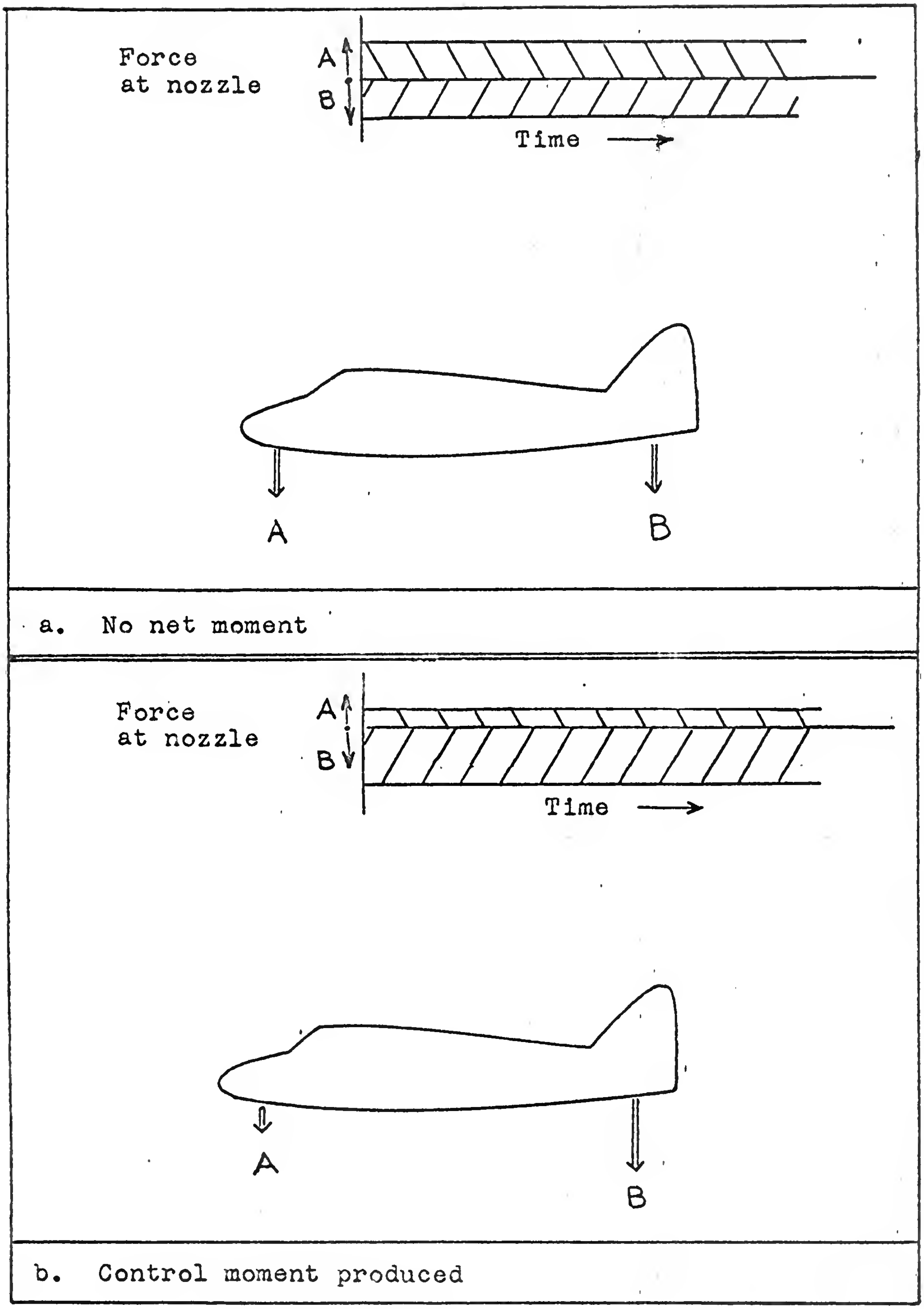


FIGURE 4

CONTROL MOMENT PRODUCED

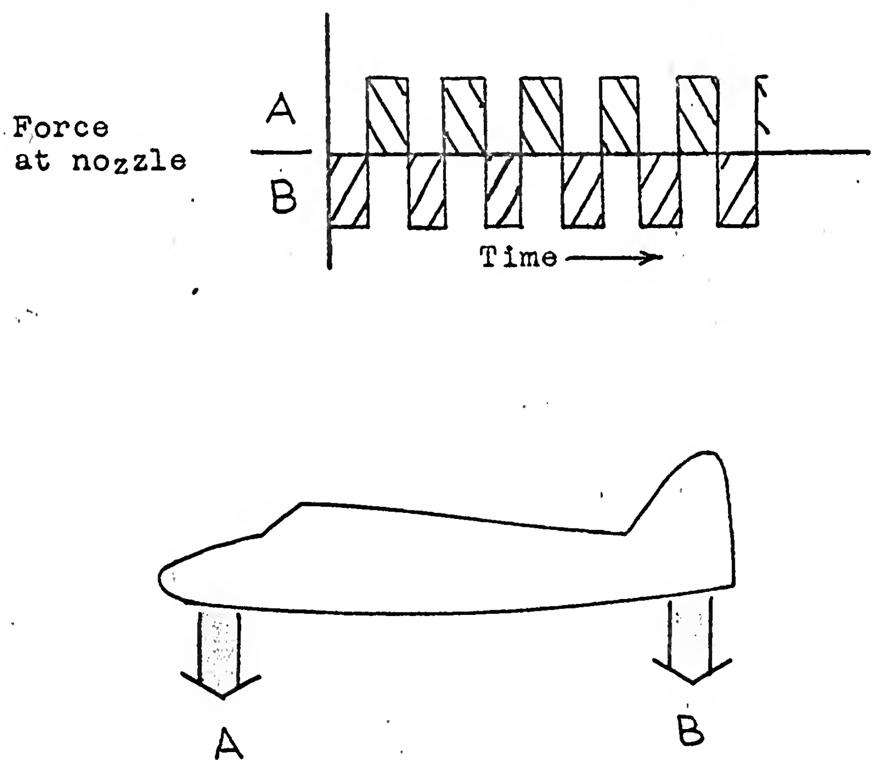
BY CONSTANT-BLEED NOZZLES

between each of the nozzles, as shown in Fig. 5a. The pulse frequency must be sufficiently high so that it does not manifest itself in an oscillation of the aircraft. The required moment can be produced with no net total force change in two ways: As depicted in Fig. 5b, the force produced by each nozzle is the same, but one acts over a longer time increment than the other; as shown in Fig. 5c, the forces act over the same time increment, but the magnitudes are varied. The latter is the more widely-used technique. A nose-up moment is produced in both examples.

The methods depicted in Figs. 4 and 5 are equally applicable to roll and yaw; they may also be used with bi-directional nozzle pairs, although a net force change will result.

The disadvantages of the bleed air jets are that they require engine bleed air and additional plumbing is required to get the air to the nozzles. The former is negated in the case of aircraft utilizing separate powerplants for horizontal thrust in that these engines can provide the control air with no degradation in lift thrust.

A second method of providing control forces is by the use of separate propulsive units near the aircraft extremities. If these units are utilized to provide lift thrust, the only disadvantages are the additional plumbing required, if any, and possible interference with other aircraft components, such as landing gear. If the units do not contribute to lift, then the additional weight, complexity, and fuel requirements may make their installation undesirable.



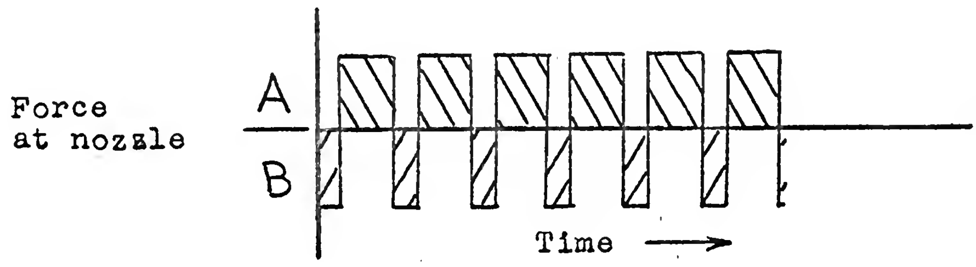
a. No net moment

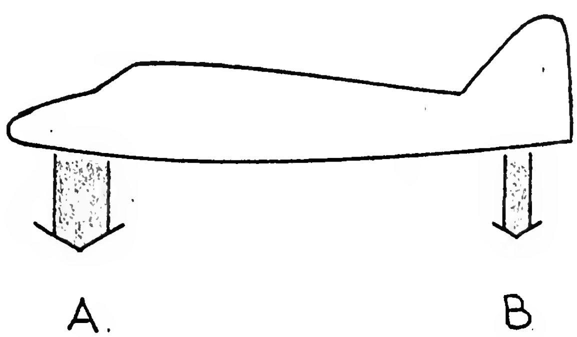
(Force vector length represents magnitude, width represents pulse duration.)

FIGURE 5

CONTROL MOMENT PRODUCED

BY PULSE-JET NOZZLES





b. Moment produced by pulse-length modulation

(Force vector length represents magnitude, width represents pulse duration.)

FIGURE 5

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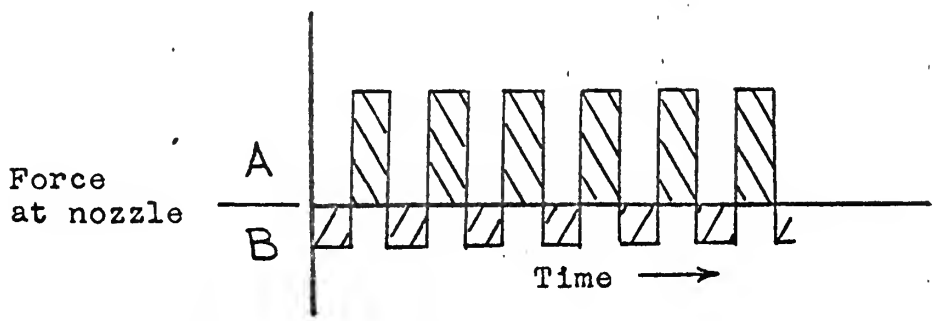
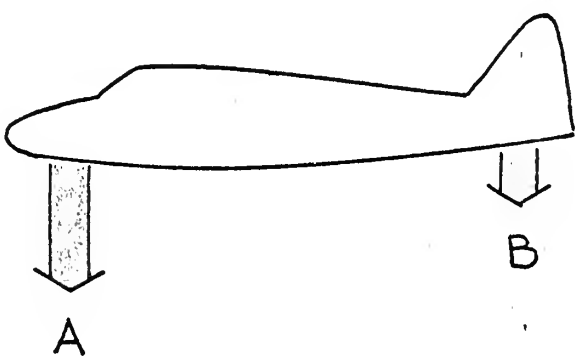




c. Moment produced by force modulation

(Force vector length represents magnitude, width represents pulse duration.)

FIGURE 5

(Concluded)

A third method is by utilization of differential thrust. A problem with this method is that response is not uniform at all throttle settings, but is usually better at high settings. Thrust modulation is usually achieved on tip-turbine fans by controlling the area of the scroll. Another drawback with thrust-tilting types of aircraft is the interaction between roll and yaw caused by differential thrust at intermediate tilt angles. This problem and proposed solutions will be discussed in more detail later in this section.

Finally, control moments may be produced by turning the slipstream or engine exhaust using vanes or deflectors; by tilting or gimballing propulsive units; and by placement of aerodynamic controls in the slipstream.

Applications of the various methods to control about each of the three axes will now be considered in turn.

Pitch control at zero and low speeds.

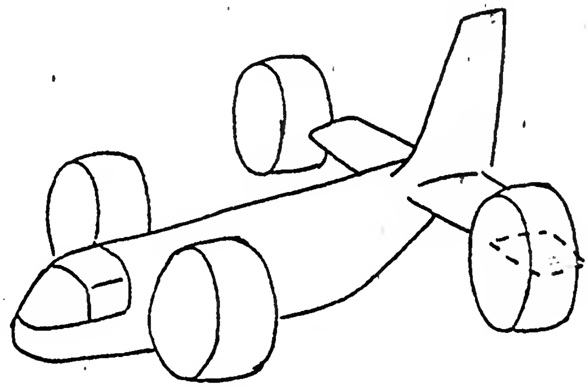
Pitch control nozzles of the continuous-flow or pulse-jet type have been extensively used to date, almost always in pairs, with downward-directed flow at nose and tail. The control thrust has usually provided a total of five to ten percent of the aircraft weight. A common scheme is to have a centralized collector chamber with ducting to the nozzles with integrated control valves. A control movement in pitch moves the valves, increasing the thrust from one nozzle and decreasing the thrust from the other so that a control moment is produced with no appreciable change in total lift.

A fan or propeller mounted at the tail of the aircraft has also been utilized for low-speed pitch control. Thrust is modulated by means of changes in propeller or fan pitch. A problem which has arisen from this type of control is that if the tail fan is in close proximity to the horizontal tail, loads are induced on the tail which cause large elevator hinge moments. Another configuration has a lift engine or ducted fan in the nose of the aircraft. The thrust from this unit is modulated by control stick movement, and since it provides a relatively large percentage of lift thrust, the main propulsive units must also be regulated to maintain nearly-constant total thrust.

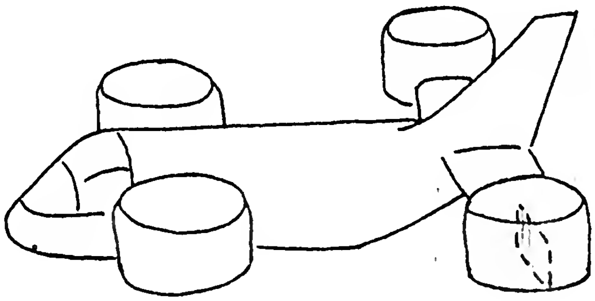
Differential thrust can be utilized for pitch control with the four-unit tandem arrangement, such as is depicted in Fig. 6. The moment is produced by differential thrust of the fore and aft units, the total thrust remaining constant.

Another proposal which must be considered as differential thrust, but which has not seen much application, is to vary the thrust output across the propeller disc of a tilt-prop or tilt-wing configuration. This can be accomplished by varying the propeller blade angle sinusoidally around the disc. A comparison between rigid and flapping blades has shown the rigid configuration to be more effective in producing changes in pitching moment [54].

Thrust diverters and control vanes located in engine exhaust have also been utilized for pitch control. The main



Cruise Configuration



Takeoff and Landing Configuration

FIGURE 6

FOUR-DUCT TANDEM ARRANGEMENT

advantage of this type of control is its simplicity; its main disadvantage is the resultant change in total lift force.

Roll control at zero and low speeds.

The discussion of nozzles for pitch control is equally applicable to roll control, except that the total nozzle forces are considerably lower, usually on the order of one percent of aircraft weight.

Differential thrust is widely used for configurations having thrust units sufficiently far outboard. In four-engine configurations, usually only the outboard powerplants are modulated. Tilt-wing aircraft vary thrust by varying propeller pitch.

Some tilt-duct research aircraft have used variable inlet guide vanes for thrust control. These vanes are arranged radially, and their movement changes the effective angle of attack of the fan blades, thereby affecting the thrust output. However, studies indicate that the order of effectiveness of methods of varying ducted fan thrust is variable duct geometry, variable-pitch fan, and adjustable inlet guide vanes [35].

Yaw control at zero and low speeds.

Horizontally directed nozzles in the nose and/or tail have been utilized for yaw control. Another scheme has been to gimbal the pitch nozzles when they are situated on the bottom of the fuselage as depicted in Figs. 4 and 5. For example, if a nose-left yawing moment were desired, the control signal would cause the nose nozzle to be swung to the right and the

tail nozzle to be swung to the left. The main disadvantage of this arrangement is the loss of lift thrust incurred at large nozzle deflections.

A separate tail fan or propeller can be utilized for yaw control. The primary drawback to this scheme is that its weight represents a penalty when not in use at cruising speeds.

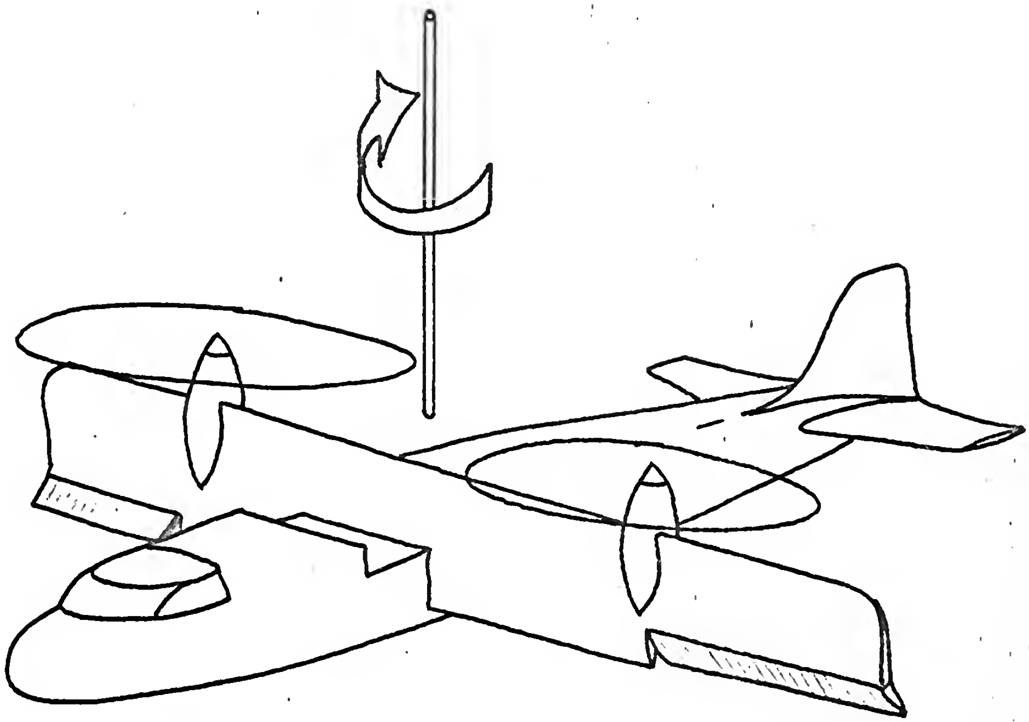
Yawing moments can also be provided by differential tilting of propulsive units such as wingtip-mounted ducted fans or jet engines. To allow for extreme deflections and maintenance of lift thrust, it is required that the units be operating at less than full power, or that they be capable of operating at overload or overspeed conditions for short periods of time.

Thrust diverters or vanes can be utilized in engine exhaust for yaw control in the same manner as was discussed for pitch control.

With tilt-wing configurations, the ailerons can be utilized for yaw control when the wing is up, as depicted in Fig. 7. For four-engine tilt-wing configurations, tests have indicated that more effective control can be realized by actuating the flap as an aileron, or by employing a double-hinged flap and utilizing the after portion of the flap as an aileron [45]. The same effect can be provided in tilt-duct installations by means of vanes or elevons in the duct exhaust.

Transfer of control in transition.

An item that must be resolved in many of the VTOL configurations is the change in direction of the moment vector as



Aileron deflection produces nose-right moment

FIGURE 7

YAW CONTROL IN HOVER BY MEANS OF

AILERON DEFLECTION

conversion takes place during transition. For example, consider a tilt wing aircraft which utilizes differential thrust for roll control and aileron deflection for yaw control while hovering. If no provision were made for changeover, the pilot would find that in level flight, a lateral stick motion would produce yaw, and rudder motion would produce roll. Several solutions to this problem have been proposed, all of them automatic. Some have been angle-of-attack controlled and some varied as a function of airspeed, but the most reliable and widely-used is the mechanical method. As this problem arises only with aircraft which tilt major components, the control changeover is programmed as a function of the component tilt angle. At intermediate tilt angles, a moment demand about an axis produces mixed control forces so as to produce only the motion desired. The inputs from the pilot's controls are usually transmitted through a mechanical resolving system which determines the proper control outputs as determined by the tilt angle.

An interesting phenomenon has been observed in this regard during flight tests of a 1/8 scale model of a tilt-wing airplane [22]. Differential engine thrust was utilized for roll control while hovering. During conversion, ailerons were gradually phased in for lateral control as the tilt angle decreased, but thrust changes were not phased out. Thus a rolling moment due to differential thrust alone was produced by the changes in slipstream velocity over portions of the wing, the lift and drag increasing with an increase in slipstream velocity.

and decreasing with a decreased slipstream velocity. This rolling moment was augmented by the aileron rolling moment, and the adverse yaw caused by the ailerons was in the same direction as the yaw caused by the asymmetric wing drag. This total adverse yaw tended to offset the favorable yaw caused by the thrust changes, with the result that nearly pure roll was obtained.

On some research aircraft, a control input actuated both low-speed and conventional flight controls at all times, regardless of the flight condition. This is not feasible for aircraft utilizing bleed-air control nozzles, as this represents an unnecessary reduction in engine power when in aerodynamically-supported flight. Other models secure the low-speed controls when some event occurs, such as thrust diverter angle becoming zero or closing of lift engine intake doors. This is undesirable, since it represents a large change in stick force gradient with a small change in airspeed. It appears then that what is required is either an automatic controlling of artificial stick forces, or a programmed phaseout of low-speed controls as aerodynamic controls become more effective.

Control power and handling qualities.

Many of the VTOL aircraft flown to date, which have been primarily research machines, have been seriously lacking in control power about one or more axes. The need for powerful control systems stems partly from a lack of stability in hovering and low-speed flight, and partly from the requirement that a VTOL aircraft be capable of precision maneuvering in confined

areas and in turbulent wind conditions. It is also imperative that control power available be independent of propulsive unit power settings.

As of this writing, there are no specific quantitative handling qualities criteria for VTOL aircraft, such as exist for conventional airplanes and helicopters. These existing requirements are applicable to the hover and conventional flight regimes, but cannot describe the specifications for flight in the transition speed range. This is primarily due to the relatively limited flight experience in this portion of the operating envelope.

Recommendations have been made for handling qualities criteria, but many of the quantitative data are merely proposals, some are based on simulator studies, and some were obtained by extrapolation of helicopter requirements [19]. These helicopter requirements are not directly applicable to other VTOL aircraft in transition, as it is generally considered that helicopters do not perform a well-defined transition, but are in a modified hovering condition, even when translating.

An important factor is the lack of understanding of the desirable relations between control sensitivity, damping, and response to external disturbances. Other areas where information is insufficient to establish a firm quantitative requirement include: dynamic stability in the transition regime; hovering steadiness; effects of acceleration and deceleration in transition; and descent rates and flight-path angles in steep approaches.

4. General Stability Problems Associated With Hovering and Low-Speed Flight

Hovering.

The aerodynamic properties of a given configuration have negligible influence on its hovering stability. This can best be envisioned by considering a brick being held aloft on a jet of air. The VTOL aircraft while hovering is at best neutrally stable, and may be unstable in some respects, its response characteristics thus being determined primarily by the ratio of the applied moment or force to the inertia of the system. This neutral stability of attitude is due to the lack of pendulous stability such as is displayed by balloons and ships. In their case, a displacement from the vertical offsets the gravitational and buoyant forces, thus producing a righting or restoring couple. In the case of the VTOL aircraft, the lift vector is displaced with the airplane and still acts through the center of gravity; thus no restoring couple is produced.

Another dynamic stability peculiarity of many of the VTOL airplanes which have been flown to date is the presence of a large dihedral effect, C_{l_β}. The effect has been so strong in some instances as to be divergent, and the loss of at least one research machine is directly attributable to this divergence. This problem has been aggravated by the fact that the oscillations have generally exhibited periods on the order of less than five seconds; in many cases this was very near the natural period of the aircraft, resulting in reinforcement of the motion.

Gyroscopic effects are often ignored in calculating the dynamic stability characteristics of conventional aircraft as they are insignificant compared to the control power and damping available. This cannot be done with VTOL aircraft, however. As the airspeed approaches zero, so does aerodynamic damping; large excesses in control power are not anticipated due to the weight and power requirements for the provision of same. Also, VTOL aircraft require a larger thrust-to-weight ratio than do conventional types; therefore, other factors being equal, either engine dimensions and weight are increased, or the number of engines for a given airplane size is increased. Both of these factors increase angular momentum.

For airplanes having horizontal propulsive units, such as vectored-thrust configurations, the cross-coupling is between pitch and yaw. For a dual-propulsion aircraft, with the lift jets oriented vertically, the cross-coupling is between pitch and roll. The tilt-jet configuration can suffer cross-coupling about all three axes at intermediate tilt angles.

It has been found that the magnitude of a coupled response which will occur is inversely proportional to the aircraft moment of inertia about the coupled axis [37, 40]. Various methods of eliminating or minimizing cross-coupling are available; artificial stabilization, counterrotating engines (two engines rotating in opposite directions), and contrarotating engines (one engine having various components rotating in opposite directions). In the case of the first two methods, failure of the stabilization system or one of the engines will cause the

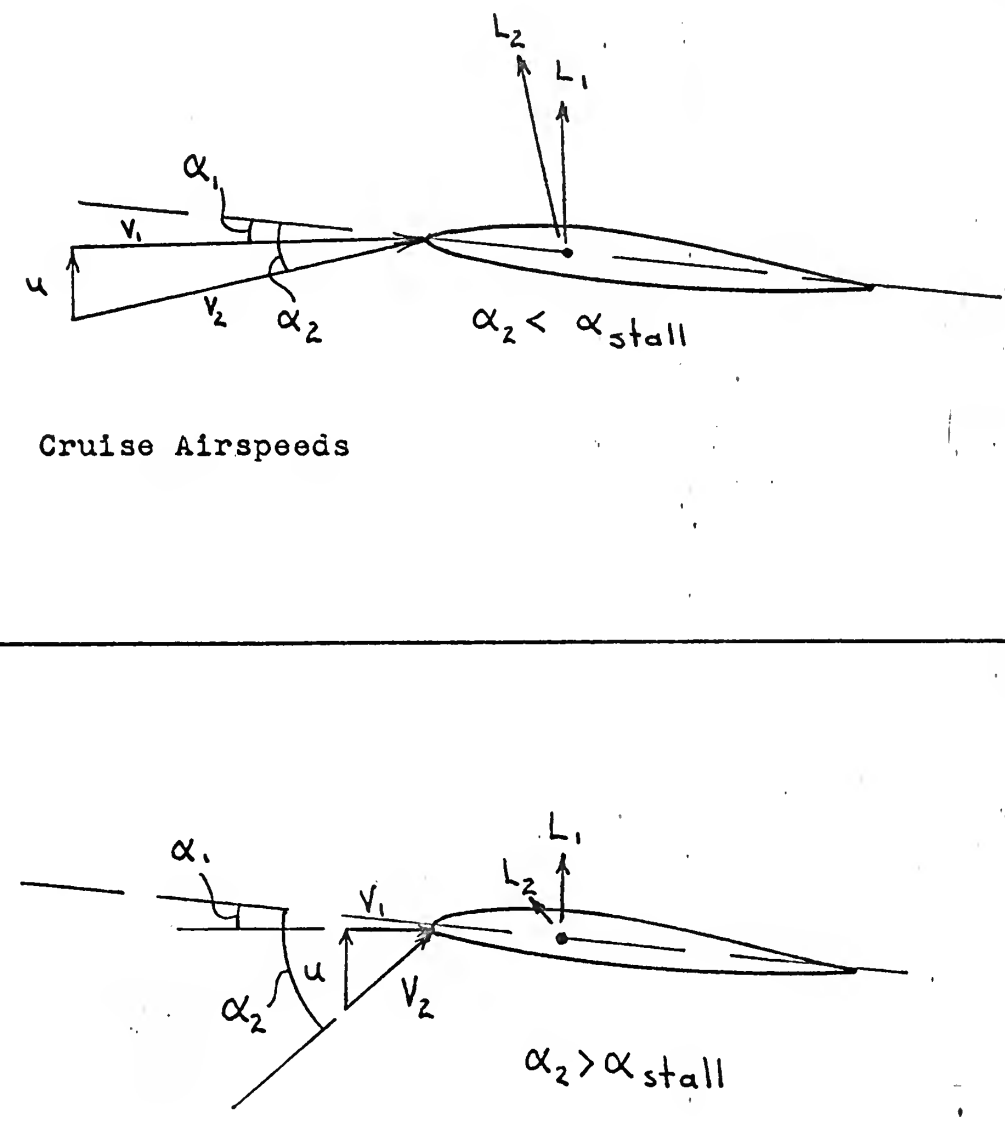
cross-coupling effects to become apparent. Contrarotating engines are necessarily more complex and heavier than their conventional counterparts.

Very low speeds.

The stability characteristics of VTOL aircraft at very low speeds cannot usually be defined in terms of the familiar stability derivatives. Most available NASA reports give qualitative descriptions of the airplane's stability characteristics; those which did compare calculated values of certain of the derivatives with experimental values often discovered large unexplained discrepancies.

In instances where aerodynamic components are located in a slipstream, force and moment coefficients cannot be based on freestream dynamic pressure. This is due to the fact that relatively large forces and moments can be produced, even though the freestream velocity decreases to zero. Thus the coefficients go to infinity and become meaningless. An alternative used by the NASA is to base the coefficients on the dynamic pressure occurring at some arbitrary point in the slipstream.

The rate damping derivatives, which are the coefficient of rolling moment due to rolling angular velocity (C_{l_p}), the coefficient of pitching moment due to pitching angular velocity (C_{m_q}), and the coefficient of yawing moment due to yawing angular velocity (C_{n_r}), have very low values at low speeds. The reason for this can best be appreciated by referring to Fig. 8.



a. Cruise Airspeeds

b. Very Low Speeds

u is relative wind due to angular velocity

FIGURE 8

EFFECT OF ANGULAR VELOCITY ON LIFT

At normal airspeeds, rate damping is provided by the increase in lift due to the inducement of or increase in angle of attack caused by an angular velocity. However, as depicted in the lower portion of Fig. 8, an angular velocity at low forward speeds can increase the angle of attack past that corresponding to stall, and the net force on the surface might decrease, resulting in very poor damping; these very large angles of attack can also result in autorotation, with attendant negative damping, or divergence.

The directional stability derivative, C_{n_β}, is also poor due primarily to low dynamic pressures. This directional instability, coupled with the large dihedral effect previously discussed, has resulted in very serious Dutch roll problems in several airplanes. Also, it is not uncommon with VTOL aircraft to have the fuselage, and hence usually the principal axis of inertia, at large angles with respect to the flight path. This axis inclination is usually destabilizing for the Dutch roll, and tends to aggravate the problem.

At the speeds under consideration, air can be considered as incompressible, and hence there are no Mach number effects. However, Reynolds number effects become quite significant. At the low Reynolds numbers under consideration, the transition of the boundary layer flow from laminar to turbulent occurs well back on the airfoil. This increases the pressure drag coefficient, causing stall to occur at lower angles of attack. Also, some airfoils have exhibited jogs in their lift curves at low Reynolds numbers [21]. The lift curve slope, C_{L_α}, can

thus no longer be taken as constant at low speeds, but must be investigated for variations with Reynolds number and angle of attack. This is further complicated by the fact that Reynolds number effects are most pronounced at low values, being practically non-existent by the time a value of 3×10^6 has been achieved. It can be seen that the many stability derivatives whose values are a function of lift curve slope could have widely varying values at very low speeds.

For conventional airplanes, the short-period and phugoid modes of oscillation have widely different periods and have been considered to proceed independent of each other. However, at the low speeds considered here, similar periods may exist for the two modes and their combined effect on the over-all behavior of the aircraft must be considered. The combination of the short-period and phugoid modes will result in simultaneous changes in airspeed, attitude, and angle of attack, thus increasing the difficulty of extracting the roots of the characteristic equation of motion.

There have been very few theoretical analyses made of aircraft motion under the condition of very low speeds; only one was found in this survey [9]. Almost all information available are as a result of model testing, or data obtained from VTOL research aircraft.

Instrumentation.

The ease and precision with which a pilot can perform a given task, and hence his rating of an aircraft's handling qualities, depend to a great extent on the type, quality, and

precision of the instrument display available to him. Instrumentation used in conventional aircraft will be of use to the VTOL pilot, but these must be supplemented by extremely sensitive, and in some cases new, instruments. This is especially true in view of the stability deficiencies previously discussed. As these aircraft possess a hover capability, it must be considered that they may be required to hover under instrument conditions, however undesirable this may be. To accomplish this, precision attitude indicators, including heading, are required. An airspeed indicator capable of indicating speeds accurately and sensitively down to and including zero, and even "negative" airspeeds will be required. This is to help the pilot prevent inadvertently achieving rearward flight, which is highly unstable for most VTOL aircraft. A sensitive, instantaneous rate-of-climb indicator is required, and a precision height indicator, such as a radar or radio altimeter. A sideslip indicator would be required to prevent undesirable sideward excursions while in hover. It has also been found that instrument approaches at slow speeds can often not be performed precisely without continuous reference to a sideslip indicator [53].

5. Specific Problems Encountered to Date

Tilt-wing and deflected-slipstream aircraft.

For reasons previously discussed, a pure deflected-slipstream VTOL aircraft is not feasible. However, flight experience with research aircraft has shown that this

configuration experiences a large nose-down pitching moment during transition, caused by the large flap deflections necessary. Of various flap arrangements, the order of increasing magnitude of this moment is; a sliding flap with a rear plain flap, a plain flap with auxiliary turning vanes, and a slotted flap. The addition of a leading edge slat reduced the nose-down moments, as well as increasing the slipstream turning angle.

Full-span leading-edge slats also alleviated the stall problem associated with this mode. This problem is illustrated in Fig. 9, which depicts schematically the wing angle of attack at partial conversion angles for the level flight, climb, and descent conditions. The vector V_f represents the flight velocity and the vector V_s represents the average slipstream velocity. The resultant vector V_r is the relative wind experienced by the portion of the wing within the slipstream. Fig. 9 is depicted for a constant airspeed and wing attitude relative to the horizontal. In a descent, the power is reduced, thus reducing V_s, and the freestream direction is changed. These effects may combine to increase the angle of attack to beyond stall. For the climb condition, the velocity changes are in the opposite sense and the angle of attack is accordingly reduced.

This wing stalling limited the angles of descent attainable without encountering unsteady flight, and wing stall could be induced in level flight at low airspeeds merely by a reduction in power.

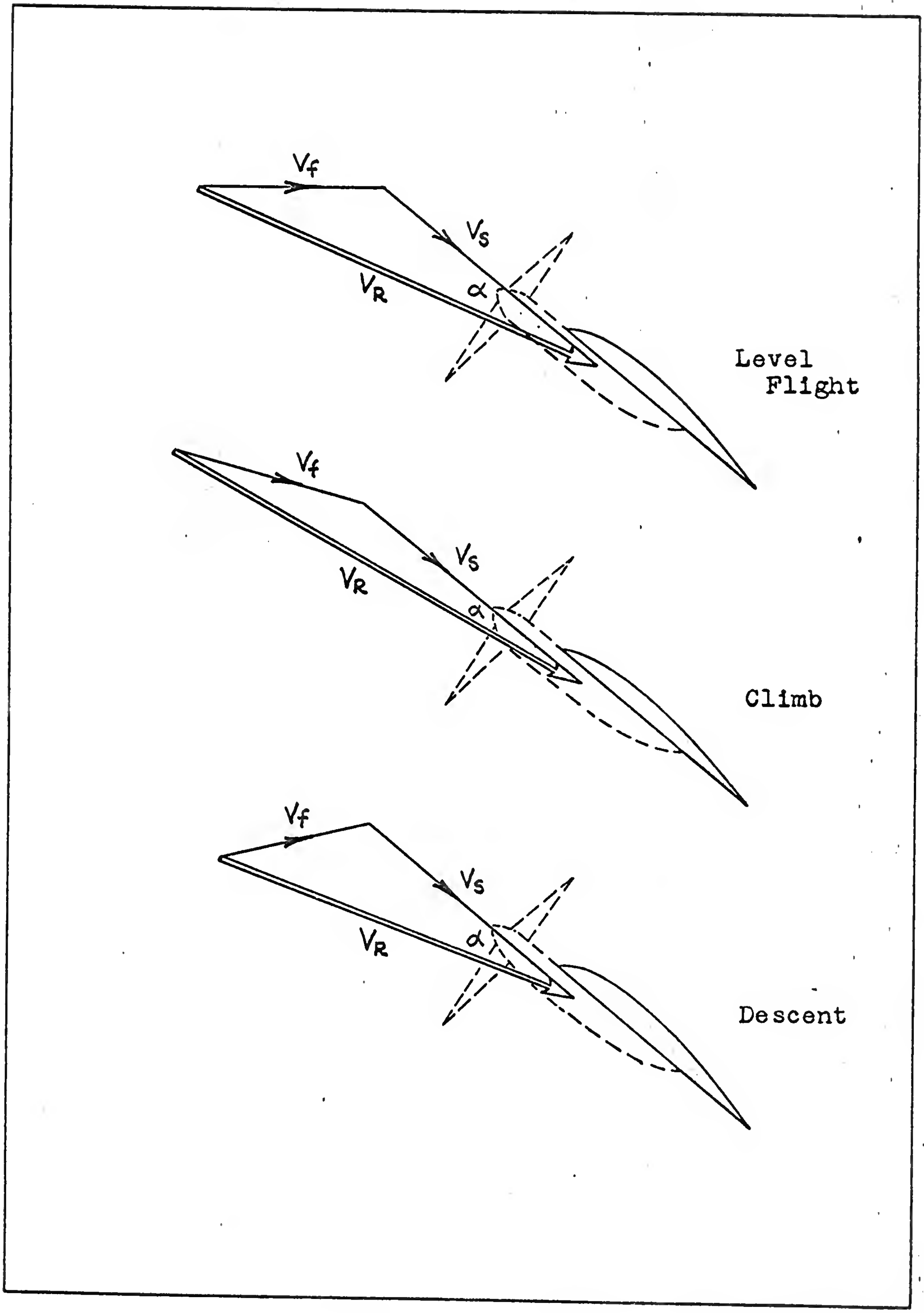


FIGURE 9

WING ANGLE OF ATTACK AT PARTIAL CONVERSION ANGLE

Tilt-wing aircraft exhibit appreciable nose-up pitching moments during transition at wing incidence angles of from approximately 60 to 90 degrees. This moment is caused primarily by the center of thrust being located well forward on the propeller disc at these incidence angles. The pitching moment was aggravated with the fuselage in a nose-low attitude, and relieved with the fuselage in a nose-high attitude.

The severity of this pitching moment on flying models and full-scale aircraft was found to be less than anticipated from wind-tunnel tests. The difference is due to the fact that transition in wind-tunnels is of necessity at zero airplane acceleration. A longitudinally accelerating transition reduced the nose-up pitching moments for the configurations for which the comparison was made. Conversely, decelerating transitions enhanced the moment, and it was required that they be performed much more gradually.

Another factor influencing tilt-wing stability, and deflected-slipstream as well, is the large values of downwash angle, ϵ, associated with these configurations. The large changes in ϵ encountered during transition would produce large changes in the pitching moment due to the tail. This indicates a possible requirement for a variable-incidence horizontal tail. Also, the downwash angle would become largely dependent on angle of attack at low airspeeds. This would cause the downwash factor $(1 - \frac{d\epsilon}{d\alpha})$ to approach zero; since the contribution of the tail to longitudinal static stability varies directly with the

value of $(1 - \frac{d\epsilon}{d\alpha})$, the tail would become ineffective in contributing to this phase of aircraft stability.

Wing stall adversely affects the aircraft handling qualities, and Fig. 9 and the associated discussion are equally applicable to tilt-wing configurations. Devices which improve the stall characteristics are flaps, slots and slats, leading edge droop, and adjusting the angle of incidence between the propeller disc and the wing zero lift line.

A comparison has been made of the stability and control effects of rigid and flapping propeller blades [44]. The results showed that the rigid-propeller configuration developed smaller nose-up pitching moments and also provided greater damping in pitch than the flapping-propeller configuration.

From the preceding discussion, it would appear that the combination tilt-wing/deflected slipstream configuration would be desirable from the standpoint of reducing transition pitching moments, as well as the reduction in power required that was previously discussed. Investigation has shown that proper programming of flap deflection with tilt angle reduced the nose-up pitching moments [45, 46]. By also programming the incidence of the horizontal tail, variations in pitching moment throughout the transition speed range could be virtually eliminated. Control power available for maneuvering would thus be constant throughout transition.

Tilt-duct aircraft.

A fundamental design problem encountered with ducted fans is the difference in required duct inlet shape for good

efficiency in hover, and that required for good efficiency in cruising flight. This is illustrated in Fig. 10. A well-rounded inlet lip is required for hovering flight to provide smooth air flow into the duct and a sufficiently large capture area. A relatively thin inlet lip is desired for cruise conditions in order to reduce aerodynamic drag. Such a lip would cause flow separation in hovering and at partial conversion angles. Some compromise must be made in the design of the inlet lip, or provisions made for a variable-geometry duct. The available literature indicates that all present ducted-fan configurations, both flying and proposed, are utilizing fixed-geometry compromise ducts.

The ducted-fan configurations tested have experienced large nose-up pitching moments during transition. This moment is primarily due to the large lift produced on the forward lip of the duct in turning the airstream downward through the duct. This moment is relieved in accelerating transitions, and reinforced in decelerating transitions.

Flow from the duct has a large influence on downwash at the tail. The downwash angle has been found to be primarily a function of duct angle. Due to these large variations in flow at the tail, installation of a variable-incidence horizontal tail was required in order to provide sufficient trim and control during transition.

It has been found that the nose-up pitching moment can be significantly reduced by the installation of a vane in the duct exhaust [34, 35]. Deflection of the vane produces a

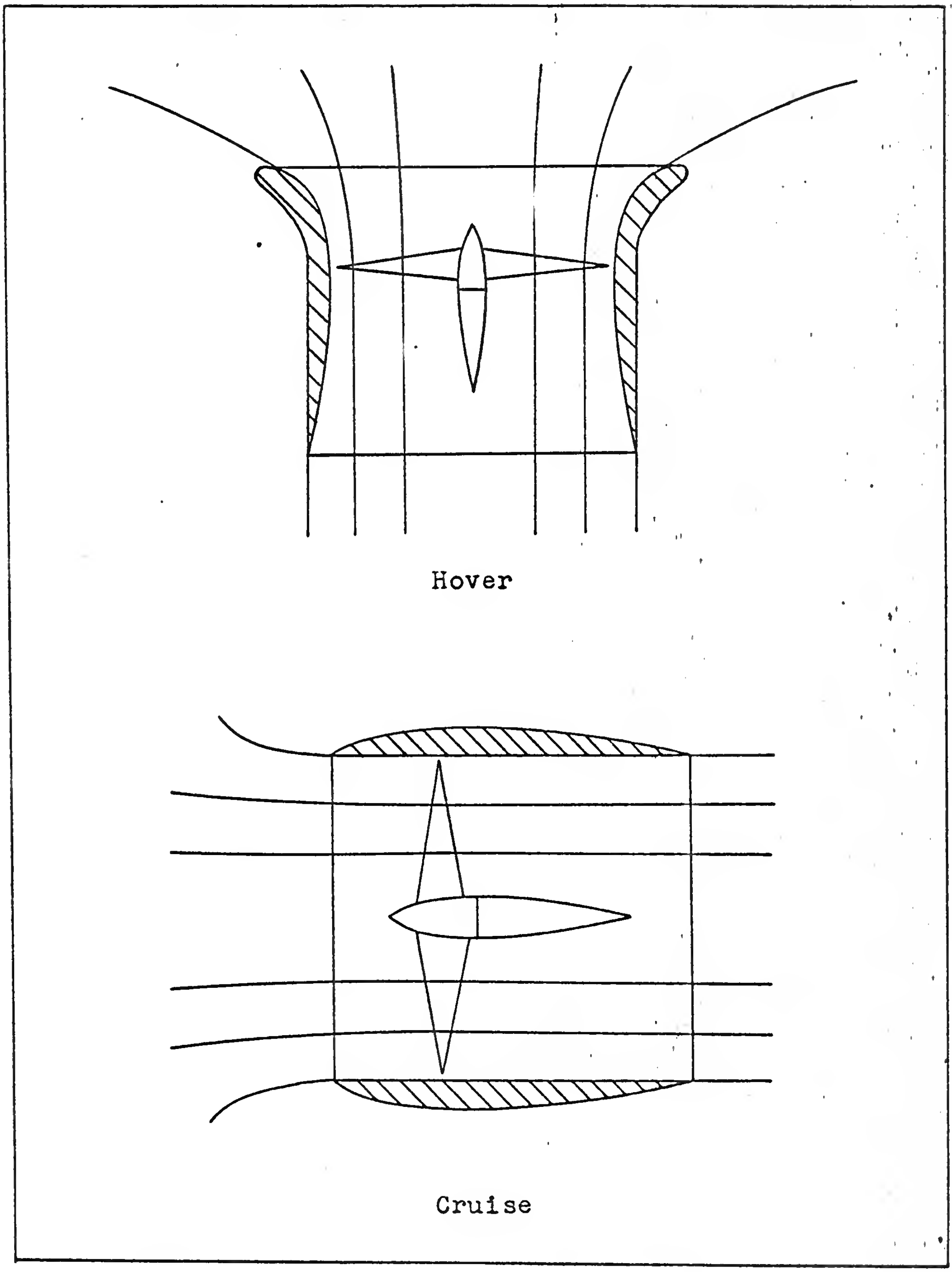


FIGURE 10

DESIRED DUCT INLET LIP SHAPE

moment counteracting the moment of the duct alone. The vane has little influence on the downwash angle at the tail, however, and does not remove the requirement for the variable-incidence tail.

Due to the absence of duct moments in hover and at high speed, it is necessary to vary the vane deflection angle with duct tilt angle. From the standpoint of ease of operation, it would be desirable to program both stabilizer indidence and vane angle to automatically vary as a function of duct tilt angle.

The wingtip-mounted duct causes stalling, under certain flight conditions, of the portion of the wing adjacent to the duct. This stall has been encountered in both level flight and descents at duct angles greater than 30 degrees. The stall is believed to be induced by increased vortex action at the ducts. The spanwise lift distribution is altered by the increased lift provided by the ducts. This causes an increased vortex action at the ducts, which induces an increase in angle of attack on the portion of the wing adjacent to the ducts.

Even at low dynamic pressures, satisfactory flying and handling qualities require that the lifting surfaces be unstalled. The stalling causes noncontrol-induced rolling motions and lateral stick "snatching". Although it is possible to avoid stalling by adjusting fuselage attitude to keep the airplane angle of attack low enough, it will probably not be operationally feasible to do so in steep descents. Also, if a transition is made from conventional to hovering flight, the

stall angle of attack must be exceeded at some stage of the maneuver. This indicates that operational tilt-duct aircraft will probably require some auxiliary lift device, such as slats, slots, or boundary layer control (BLC), at least in the wing regions adjacent to the ducts.

Buried-fan aircraft.

Early investigations indicated that serious interference effects could be encountered with some jet and buried-fan configurations in transition. The effects were shown to be due principally to the pressures induced on the bottom of a wing or fuselage which are caused by the interaction of the exiting air jet and the freestream flow. Positive pressures are generated ahead of the jet and negative pressures behind. This pressure distribution resulted in a force pair which produced a nose-up pitching moment. It was also found, with small scale wind-tunnel tests, that the negative pressures produced a force which was greater than that produced by the positive pressures, resulting in a net loss of lift, called "lift droop" or "suck down".

Tests with full-scale models have shown that this loss of lift was not experienced; that in fact lift increased with increases in forward speed. This contradiction is considered to be due to adverse scale effects due to lower Reynolds numbers on the small models. It is recommended by the NASA that small-scale tests showing lift droop should be examined carefully to determine whether the effect is due to configuration or scale.

Full-scale tests have also shown that the nose-up pitching moment caused by the jet-induced pressure distribution is overshadowed by the nose-up pitching moment caused by the fan. This is caused by the location of the center of pressure on the fan being forward of the fan axis. For fan-in-fuselage configurations, an additional nose-up pitching moment is caused by the increased pressure on the rear side of the fan duct. If fan exhaust is vectored to provide some horizontal thrust, an additional moment contribution is made. For fan-in-fuselage and low-wing fan-in-wing configurations, this contributes to a nose-up pitching moment. The horizontal thrust component contributes to a nose-down pitching moment for a high-wing fan-in-wing configuration.

Tests have shown that for the fan-in-wing configuration, fan exhaust influences the lift increment caused by flap deflection. This effect is less pronounced for flaps extending well beyond the fans, and at large flap deflections. It has also been shown that vectoring of the fan exhaust increases the apparent lift-curve slope [12].

Full-scale tests have shown that moment changes resulting during transition of a fan-in-wing configuration are of the same order of magnitude as those resulting from flap extension or retraction on a conventional airplane. Fan-in-fuselage tests have shown a large variation in pitching moment with forward speed. Use of direct thrust during transition should alleviate this problem to some extent, but there is presently no data available.

Jet aircraft.

Very few references were found which pertained to jet aircraft. Those which were available indicated that most of the problems encountered to date are pertinent to a particular aircraft, not to a class of aircraft. General aerodynamic problems, such as wing stall in steep descents, are of course equally applicable to jet aircraft. Jet modes such as the diverted-thrust and tilt-jet modes have the same inlet shape problem as was discussed for tilt-duct aircraft. One airplane, the British Hawker P. 1127, alleviates this problem by utilizing an inflatable inlet lip. At hover, the lip is inflated, providing the well-rounded inlet shape desired; at high speeds it is deflated, and a low-area inlet shape results. A dual-propulsion tilt-jet airplane, the German Entwicklungsring Sud VJ 101, has high-speed inlets on its tilting main propulsion engines, and evidently accepts the duct losses incurred in hovering flight.

The various thrust components must be so arranged that the resultant thrust vector during transition passes through or near the airplane center of gravity, or large moment variations will result. Small-scale wind tunnel tests show that the jet interference effect produces the same effect for jet exhausts as it did for ducted-fan exhausts [47]. The loss of lift experienced was primarily a function of wing area surrounding the exits. The loss was greater with greater area, presumably because the net negative pressure thus has a larger area over which to act. The nose-up pitching moment increased

with an aft movement of the wing (either from placement or variable sweep), again due to the wing moving into the region of greatest induced negative pressures. In view of the fact that this same effect did not manifest itself in full-scale ducted-fan tests, its applicability to full-scale jet aircraft must be questioned.

6. Autostabilization and Control

The flying qualities of present-day VTOL aircraft are widely variant. Some can be flown quite satisfactorily in hover and at low speeds with no artificial stabilization; in others it is a matter of the pilot attempting to maintain control until an immediate safe landing can be affected. However, even with the well-behaved aircraft, the previous discussions in this paper indicate that a VTOL aircraft must have some degree of artificial stabilization if it is to operate in the hovering and low-speed flight regimes under other than favorable weather conditions.

A particular VTOL autostabilization problem is that of controlling airplane attitude during an instrument approach and during transition. With a conventional airplane the angle of attack, and hence attitude, is uniquely defined for a given airspeed and gross weight. A VTOL aircraft can be partly wing-borne and partly thrust-borne. Thus there is no intrinsic control of aircraft attitude since large changes in aerodynamic lift can be compensated by changes in lifting thrust. A change

in aircraft attitude can affect the flight path however, and it is thus necessary to provide an independent attitude control.

It is evident that the pilot's control demands yield different results in thrust-supported flight than in wing-borne flight due to the virtual absence of aerodynamic damping. For example, a lateral stick displacement in conventional flight produces a roll rate; if the stick is centered, the roll rate decays and a roll angle results. A lateral stick displacement while hovering produces a roll acceleration; if the stick is centered, this may stabilize into a roll velocity. Control in thrust-supported flight thus generally involves one more integral term about each axis than is required for conventional flight control. This lack of aerodynamic damping can be made up for by control forces provided by autostabilizer response to an angular rate gyro feedback in roll, pitch and yaw.

Changeover between pure VTOL to pure aerodynamic controls during transition must be smooth for instrument flight. From a simplicity standpoint, it would be desirable that the autostabilization system not require external air data inputs such as the sensing of dynamic pressure or altitude. It is also desired that optimum performance be obtained from the system regardless of center of gravity, weight, and engine performance conditions. These features indicate that a self-adaptive autostabilization system will probably be the most effective.

A simulator study has shown that divergent motions often occur in cases of stability augmentation system failure while the pilot is engaged in a precise tracking task such as a GCA

or ILS approach [51]. This points up the need for a fail-safe or redundancy feature in an autostabilizer. The most straight-forward development is to triplicate the auto-controls and use a majority vote comparator for faulty signal rejection. Such a system can survive only one fault. Recent effort has produced a system in which each element has a failure survival capability in itself, by means of either built-in or integral redundancy. Connection of such elements into a control system provides multiple paths for control signals. Partial failure may cause slight performance deterioration, but it is highly probable that numerous internal failures will not incapacitate the system.

Automatic compensation for failure of a lift unit may also be required for some aircraft, expecially those designed for commercial use. Many of the present VTOL designs have multiple jet lift units located in pods which are mounted outboard on the wing. Failure of one of these units can induce large rolling accelerations. One solution is to automatically cut the diagonally opposite engine, at the same time increasing the thrust of the remaining engines. The obvious shortcoming to this system is the removal of an operating propulsive unit.

Providing there is adequate thrust margin available, a method which is finding wide use is group thrust compensation (GTC). With this system, each lift unit in a group which has the same roll-control moment arm has pressure taps leading to a pressure sensor. This sensor compares pressures in each of the engines and is connected through a small pneumatic actuator

to a group throttle linkage. A pressure reduction in any one engine below a predetermined value results in an increased thrust demand from the entire group. The actuator is of necessity of a fail-safe design and must be capable of being rendered inoperative until all engines are operating. The actuator is pneumatic in operation in order that it might be completely independent of the aircraft electrical or hydraulic system.

It is apparent that unless the lift units are capable of operating at high overspeed conditions, the GTC cannot compensate completely for a total engine failure. It can, however, reduce the resultant rolling moments to an acceptable level.

A logical but necessarily more complicated extension is the combination of autocontrol and group thrust compensation in a system called force and moment control. This system utilizes accelerometers and engine thrust sensors for computation of control output signals. Lack of forces due to insufficient control or control failure is supplemented or replaced by differential thrust. In the event of lift unit failure, control forces augment the differential thrust so that no resultant rolling moment is produced.

7. Conclusions

Many combinations of methods of providing a VTOL capability are available; the final choice of aircraft configuration is primarily a tradeoff of mission requirements and aircraft performance. Control forces can be provided during hover in several ways; those which have found the most favor are reaction nozzles, differential thrust, and separate small propulsive units. Some types of controls on tilting configurations provide a moment about one axis during hover, and about another axis during conventional flight. This requires a programmed changeover of required control forces during conversion in order to ensure a pure response to a given pilot's control deflection at all times.

VTOL aircraft are at best neutrally stable, and often unstable, while hovering. Airplane inertia and cross-coupling caused by engine angular momentum have significant effects on stability characteristics. A typical stability problem of many VTOL aircraft is a large dihedral effect combined with weak directional stability, which combines to provide very poor Dutch roll characteristics, including instability. Aerodynamic damping is very poor in hover and at low speeds due to stalling of aerodynamic surfaces and low dynamic pressures. Precision hovering and low-speed tasks under instrument conditions will require certain instrumentation in addition to that required for conventional flight.

Certain of the configurations exhibit stability and control problems peculiar to that configuration. The major problems, as pertinent to each propulsion mode, follow.

Propeller aircraft:

Tilt-wing aircraft.

Tilt-wing aircraft require high power during transition, and exhibit appreciable nose-up pitching moments at wing tilt angles of 60 to 90 degrees. An accelerating transition (hover to level flight) reduced these moments, and a decelerating transition (level flight to hover) enhanced them. Large changes are encountered in downwash angle, ϵ, during transition, with attendant large changes in the pitching moment contribution of the tail. Wing stall is a problem with this configuration at partial conversion angles. This wing stalling limited the maximum descent angle, and requires careful throttle manipulation, as stall can be induced in level flight at low airspeeds by a reduction in power, with resultant decrease in slipstream velocity.

Deflected-slipstream aircraft.

Deflected-slipstream VTOL aircraft require high power during hover. A large nose-down pitching moment is experienced during transition. This moment is caused by the large required flap deflections. This moment can be reduced by using flap-on-flap or slotted flap arrangements, and by use of a leading edge slat. The slat also aids in reducing the stall problem associated with this mode at partial conversion angles.

Combined tilt-wing and deflected-slipstream.

A combination of the tilt-wing and deflected-slipstream modes is advantageous. Power requirements are minimized for all phases of transition. Proper programming of flap deflection

with wing tilt angle reduced the pitching moments; programming the incidence of the horizontal tail virtually eliminated variations in pitching moment during transition.

Ducted-fan aircraft:

Tilt-duct aircraft.

A ducted fan installation requires different inlet shapes for high- and low-speed flight; this requires either variable-geometry ducts, or compromise designs. These aircraft experience large nose-up pitching moments during transition, caused by the turning of the air into the duct inlet. Downwash angle has been found to be primarily a function of duct angle, and a variable-incidence horizontal tail has been found necessary to offset large variations in the airflow at the tail during transition. The pitching moments can be significantly reduced by the installation of a vane in the duct exhaust, but this vane has practically no influence on the downwash problem. Tilt-duct aircraft experience wing stalling during transition much the same as the tilt-wing and deflected-slipstream aircraft do. In addition, the portion of the wing adjacent to the duct is stalled under certain flight conditions. This stall is believed to be caused by increased vortex angle at the ducts, which induces an increase in angle of attack on the portion of the wing adjacent to the duct.

Fan-in-wing and fan-in-fuselage.

Early small-scale wind tunnel tests indicated that serious interference effects could be encountered with some jet and buried-fan configurations in transition. These effects

manifested themselves as nose-up moments and loss of lift, sometimes called "lift droop" or "suck down". Tests with full-scale models have shown that lift was in fact increased with forward speed, and that these nose-up interference moments are overshadowed by the nose-up pitching moment caused by the fan. This contradiction is considered to be due to adverse scale effect due to low Reynolds numbers on the small models. The fan pitching moment is due to the center of pressure being forward of the fan axis; an additional moment is caused by the increased pressure on the rear side of the deep duct of a fan-in-fuselage configuration. Fans exhausting near flaps influence the lift increment caused by flap deflection. In general, magnitude of and variation in pitching moment during transition is less for fan-in-wing aircraft than for fan-in-fuselage.

Jet aircraft.

Available information indicates that most of the problems encountered to date with jet VTOL aircraft are pertinent to a particular aircraft, not to the class as a whole. Wing stall during descents is a problem with jet aircraft, as it was with the other types. Jet modes utilizing the same engines for hover and cruise have the problem of incompatability of the required duct inlet shapes for these flight conditions. Small-scale wind tunnel tests show that interference effects result in loss of lift and nose-up pitching moments. Since these effects did not manifest themselves in full-scale ducted-fan tests, the applicability to full-scale jet aircraft must be questioned.

The stability deficiencies of VTOL aircraft at hover and very low speeds result in a requirement for automatic stabilization in order to safely perform flight under instrument conditions.

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